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This report is the Final Technical Report for AFOSR Grant 89-0420, monitored by Dr James McMichael, for the period June 15, 1989 to October 14, 1992. Under this program, research was performed (a) to describe the structure of the large-scale motions in supersonic turbulent boundary layers, (b) to study the interaction of that turbulence with shock waves and strategies for controlling the interaction, (c) to differentiate between Mach and Reynolds number effects on turbulence structure in wall-bounded flows, and (d) to develoo and implement new non-intrusive diagnostic techniques. The research is aimed at providing physical insight, and scaling information, for the development of turbulence models appropriate for supersonic shear layers. The primary experimental means used in these investigations were the Rayleigh scattering technique to study the instantaneous density field, the RELIEF line tagging method to study the instantaneous velocity field, and a dual hot-wire technique to obtain simultaneous velocity and density signals.

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Covering the Period 6/15/89 through 10/14/92

"THE STRUCTURE OF TURBULENT BOUNDARY LAYERS AND SHOCK WAVE BOUNDARY LAYER INTERACTIONS"

AFOSR Grant 89-0420

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April 13, 1993

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Summary

This report is the Final Technical Report for AFOSR Grant 89-0420, monitored by Dr James McMichael, for the period June 15, 1989 to October 14, 1992. Under this program, research was performed (a) to describe the structure of the large-scale motions in supersonic turbulent boundary layers, (b) to study the interaction of that turbulence with shock waves and strategies for controlling the interaction, (c) to differentiate between Mach and Reynolds number effects on turbulence structure in wall-bounded flows, and (d) to develop and implement new non-intrusive diagnostic techniques. The research is aimed at providing physical insight, and scaling information, for the development of turbulence models appropriate for supersonic shear layers. The primary experimental means used in these investigations were the Rayleigh scattering technique to study the instantaneous density field, the RELIFF line tagging method to study the instantaneous velocity field, and a dual hot-wire technique to obtain simultaneous velocity and density signals.

1. GENERAL INTRODUCTION

1.1 Recent Highlights

Recent highlights of the research performed at the Princeton Fluid Dynamics and Gasdynamics Laboratory, and the Applied Physics Laboratory include:

1. Mixing enhancement in a supersonic free shear layer has been demonstrated using blowing normal to the direction of the principal shear. In preliminary experiments, schlieren photography and Rayleigh scattering were used to visualize the effects of air injection normal to a plane shear layer with a convective Mach number close to one. Localized blowing was found to increase the growth rate of the shear layer, the intensity of the turbulence and the unsteadiness of the reattachment shock. However, uniformly distributed air injection dic not appear to affect the flow strongly. The results suggest that three-dimensional disturbances are more effective for control than two-dimensional disturbances, and that there is a strong connection between the incoming turbulence and the shock motion at reattachment. Current work is exploring the possibility of using piezo-electric devices to generate periodic, controllable blowing rates (Jon Poggie).

2. The instantaneous validity of the Strong Reynolds Analogy in a supersonic turbulent boundary layer has been validated for the first time by direct measurement. The turbulent velocity and temperature behavior at a point in a Mach 3 turbulent boundary layer was measured using two closely-spaced constant temperature hot-wires. By operating the wires at different resistance ratios, it was possible to separate the mass-flux contribution to the hot-wire output from the total temperature contribution. Measurements were made upstream and downstream of a shock wave turbulent boundary layer interaction

generated by a 16^{o} compression corner. The instantaneous form of the "Strong Reynolds Analogy" was found to hold to within experimental error, and the correlation coefficient between temperature and velocity was found to lie between -0.9 and -1.0 (Doug Smith).

3. Measurements of the instantaneous velocity along a line have been made in a supersonic turbulent boundary layer using the RELIEF technique. The preliminary results indicate very good agreement with the mean velocity profile measured using conventional techniques. The turbulence levels given by the RELIEF method are consistently lower than the values determined using hot-wire anemometry, although the trends are in agreement. The discrepancies are probably due to errors in the RELIEF method where turbulence measurements require very accurate estimates of small displacements. Further work is in progress (J. Forkey).

4. The fractal dimension of the turbulent/non-turbulent interface has been measured using Rayleigh scattering to image the instantaneous density field (with K. Sreenivasan and R.B. Miles). Results at Mach numbers of 2.5 and 2.9 were used to estimate the fractal dimension of the density interface, and the results indicated a decrease with Mach number, where a representative value for the supersonic case was 1.2, compared with a typical value for a subsonic boundary layer of 1.35. This observation may be interpreted as a decrease in mixing across the turbulent/non-turbulent interface, and seems to support the conclusion of a reduced level of intermittency with increasing Mach number (Jon Poggie).

5. Simultaneous hot-wire and Rayleigh scattering density measurements have been made, indicating the loss of coherence as the wall is approached. Rayleigh scattering was used to visualize a streamwise slice of the instantaneous density field in a Mach 2.9 turbulent boundary layer. Just downstream of the laser sheet a hot-wire was used to monitor the mass-flux variations (which by the Strong Reynolds Analogy, and the assumption of negligible pressure fluctuations, are directly proportional to the instantaneous density variations). As each image was recorded, the corresponding hot-wire "density" signal was also recorded. The density signals from the two techniques were then compared at different heights in the layer. Qualitatively, the comparison was good in the outer half of the layer, but at lower positions the signals became uncorrelated. This effect is probably due to the presence of the ice cluster scattering centers which mimic the density when the temperature is low, but which eventually disappear as the temperature rises near the wall due to frictional heating. Quantitative comparisons are now being made since the convection velocities of the turbulent motions have been measured directly using double-pulsed Rayleigh scattering (Wolfgang Konrad, Terry Nau).

6. Detailed measurements of the mean and turbulence characteristics of turbulent boundary layers have been made over a wide range of Mach and Reynolds number. At Mach 2.9, mean velocity measurements have now been completed at Reynolds numbers based on momentum thickness of about 9,500, 22,500 and 50,000 (in addition to our "standard" case of about 80,000). At Mach 0.1, detailed measurements of the mean and turbulent velocities are nearly complete at Reynolds numbers of 5000 and 13,500 (Randy Smith,

Wolfgang Konrad).

7. The development of a line vortex in a viscous fluid has been studied analytically to show that only modest stretching rates can produce highly elongated vortices. This analysis may suggest conclusions regarding the life cycle of vortical structures in boundary layers. In particular, it may help to explain why large scale motions at low hypersonic speeds appear to have a much longer time constant than similar structures observed in subsonic flows.

8. The time evolution of three-dimensional passive-scalar structures in a low Reynolds number turbulent boundary layer has been visualized using three-dimensional reconstruction of two-dimensional images of smoke flow in air, and dye in water. In the early work by Goldstein and Smits, at a Reynolds number based on momentum thickness of about 700, the scalar field evolution was visualized in 96 time steps separated by 0.1 t^+. The visualized volume size was rather small, however, and many interesting features could not be resolved. In the present work, using dye in water, a new scanning apparatus has been developed to provide similar time resolution using a much larger volume. Preliminary results have provided considerably better visualizations, extending over volumes 1.4 x 3.4 x 4.3 boundary layer thicknesses in extent (Carl Delo, Richard Kelso).

9. The first measurements have been taken to document the onset of three-dimensionality in a supersonic turbulent boundary layer. The three-dimensionality is produced by a curved fin which generates a swept isentropic compression. Mean flow measurements have been amde throughout the flowfield, and the evolution of 8 out of the 9 components of the Reynolds stress tensor has been documented. Matching computations have been made by D.D. Knight of Rutgers University (Wolfgang Konrad).

10. An apparatus has been built to study heat transfer augmentation in fully-developed channel flow in the laminar, transitional and fully turbulent regimes. Preliminary measurements have revealed the presence of multiple instability modes in the transitional regime linked supporting the concept of scale-matched destabilization. Matching DNS computations have been made by G. Karniadakis (Mark Zagarola).

11. Chaotic advection has been studied in a complex annular geometry as a model problem for testing computational methods. Matching DNS computations have been made by D. Barkley, Y. Kevrekidis and G. Karniadakis (Arel Weisberg, Emily Moren).

12. Wavelet analysis has been used in a shock wave boundary layer interaction to discriminate the wall pressure signal generated by a moving shock from the signals generated by the wall-bounded turbulence. The scaling parameters used in wavelets allow the selective amplification of scales, and it appears that they can be used to help differentiate between shock motion and incoming turbulence (Jon Poggie).

13. A family of complex wavelet functions has been designed to identify vortical structures in turbulent flows (with J.G. Brasseur). Vortical structures have characteristic velocity signatures, no matter how the sensing probe cuts

the vortex tube. By designing a family of complex wavelets to match the signatures generated by the different velocity components by a moving vortex, we hope to use wavelet analysis to help identify the structural components of the organized motions in turbulent boundary layers (Randy Smith).

14. Filtered Rayleigh scattering techniques have been developed to provide two-dimensional velocity, temperature and density maps in supersonic turbulent flows. The method employs a narrow linewidth atomic or molecular filter placed in front of the detector array. By tuning the illuminating laser, the velocity information can be obtained by monitoring the Doppler shift, and the temperature can be recovered from the extinction profile. The technique is also useful for suppressing background scattering in the conventional Rayleigh imaging technique. The method has been extensively tested and it has been applied at the Gasdynamics Lab in the 8"x8" Mach 3 tunnel and in a small Mach 5 facility (J. Forkey, J. Poggie). It has also been applied extensively by Professor Samimy at Ohio State University.

15. Quantitative comparisons have been made between convection velocities measured using hot wire and double-pulsed Rayleigh scattering images. Double-pulsed Rayleigh images have also been obtained showing the distortion of turbulent motions as they pass through a shock (S. Cogne, J. Forkey).

16. The RELIEF technique has been significantly simplified by the use of a Raman cell. Instead of aligning two frequency-matched laser beams in time and space to tag the flow, a single laser beam is passed through a newly-developed Raman cell to produce pump and Stokes beams which are automatically frequency matched and temporally and spatially overlapped (B. Zhang, I. Glesk).

17. The RELIEF technique was used to measure the velocity profile, the turbulence intensities, the lateral correlation function and the lateral second-order structure function in a free jet flow. The spectrum in the inertial range was found to have a slope of 0.669 at apoint 35 diameters downstream of the exit, in good agreement with previous data (B. Zhang, D. Zhou).

18. Measurement of turbulence structure of scales of motion down to 20 micrmeters has been demonstrated using the RELIEF technique (B. Zhang).

19. The RELIEF technique was used to measure local temperatures. A thin line is written in air by vibrationally exciting oxygen molecules using the RELIEF technique. The rate at which the diameter of the line increases is then measured and the temperature is determined by knowing the temperature dependence of the diffusion rate (B. Zhang, D. Zhou).

Support under the present Grant (89-0420) has contributed to the results given under Items 1 to 8, and 12 to 19.

1.2 Current Activities

In the coming year, we will continue to study some of the projects identified above. In particular,

1. We will continue to study mixing enhancement in a supersonic free shear layer has been demonstrated using blowing normal to the direction of the principal shear. We will use Filtered Rayleigh scattering to visualize the shear layer in the transverse direction, and thereby identify the most effective blowing conditions. Then we will attempt to implement, with the help of Professor Ari Glezer at the University of Arizona, piezoelectric actuators placed at the lip of the backward-facing step to enhance our control, particularly in generating suitable three-dimensional disturbances. We will make extensive use of Rayleigh scattering, Filtered Rayleigh scattering and RELIEF diagnostics to investigate the flowfiled structure. (Jon Poggie).

2. We will continue to make measurements of the instantaneous velocity along a line in a supersonic turbulent boundary layer using the RELIEF technique, especially to resolve the differences between the hot-wire and RELIEF measurements of density fluctuations.

3. Quantitative comparisons will be made between simultaneous hot-wire and Rayleigh scattering density measurements using double-pulsed Rayleigh scattering to measure the convection velocities of the turbulent motions directly (Terry Nau).

4. At Mach 2.9, we hope to begin measurements in very low Reynolds number flows. Two aspects will be studied: forced transition (turbulent spots) and low Reynolds number turbulent boundary layers (Craig Schuitevoerder, Terry Nau).

5. The time evolution of three-dimensional passive-scalar structures in a turbulent boundary layer at a Reynolds numbers of 525 and 1400 using dye in water will be completed. Visualizations at higher Reynolds numbers will begin, as will the quantitative analysis of the lowest Mach number case. Other cases to be studied include jets in cross flow, and turbulent wakes (Carl Delo, Richard Kelso, Genevieve Nestor, Bill Dawes).

6. Wavelet analysis will continue to be developed for the analysis of experimentally obtained turbulence signals. The use of complex wavelets to help identify the structural components of the organized motions in turbulent boundary layers will also begin (Jon Poggie).

The coming year will also see a great deal of facility construction as we prepare for three major new projects.

For the study of hypersonic turbulent boundary layers, we are constructing a Mach 8 boundary layer facility to perform fundamental boundary layer and shock wave boundary layer experiments. This work is being done by Professors Smits, Miles and Brown, and it is being funded by AFOSR (Dr.

Sakell), with substantial support from Princeton University to help construct the new facility. The vacuum system using high pressure air ejectors is currently being installed, and it is expected to be ready for use by June of this year. The Mach 8 facility itself will not be ready until perhaps January of 1994, but in the mean time we will use the vacuum system to operate the Mach 3, 8"x8" LTVG (Low Turbulence Variable Geometry) tunnel at very low Reynolds numbers to study bypass transition and low Reynolds number turbulent boundary layers. The transition and boundary layer studies will be extended to Mach 5 by the construction of a new nozzle for the LTVG, and finally to Mach 8 upon completion of the new facility (Terry Nau, Jean-Francois Lucas).

We are also studying problems in Aerothermochemistry under a grant from the AFOSR URI program monitored by Dr. Tishkoff. This is a major new program, involving Professors Brown, Smits, Miles, Dryer, Law and Jameson, as well as Drs. Lempert and Yetter. With this support, we are expanding our facilities to study supersonic combustion (Mach 3) in experiments designed to improve our understanding of reacting flows where the initial flows are either simple (laminar and steady) or complex (turbulent boundary layers, mainly three-dimensional, with significant levels of streamwise vorticity).

Finally, we will study incompressible turbulent flow at very high Reynolds numbers and over a very large range of Reynolds numbers to provide definitive experimental results against which to examine our current understanding of turbulence. This experiment will be performed at the Gasdynamics Lab, in cooperation with Professors G.L. Brown and S.A. Orszag. The emphasis initially is on wall-bounded flows but future work will include studies of wakes and other free shear flows. All previous direct computational studies of turbulent flow have been performed at low Reynolds numbers, and most experiments at moderate Reynolds numbers and over a limited Reynolds number range. As a consequence, we have little definitive information regarding high Reynolds number behavior, and the reliability of extrapolating from low Reynolds number. We do not know how well our scaling laws for the mean and turbulent fields continue to apply, or if the separation in scales at very high Reynolds number can provide new insight into the underlying physics of wall-bounded flows (Mark Zagarola).

The experiments will be carried out in fully developed pipe flow at a maximum Reynolds number based on pipe diameter and mean velocity of 5 x 10^7. The lowest Reynolds number will be 10^3, and therefore the experiments will cover Reynolds numbers from the lowest value for turbulent flow in a pipe to the highest value ever measured. The previous highest pipe Reynolds number was 3.2 x 10^6, obtained by Nikuradse in 1932, and his measurements were restricted to mean flow quantities. The highest Reynolds numbers where turbulence quantities were measured were all less than 10^6 (4.2 x 10^5 by Laufer 1954, 4.5 x 10^5 by Coantic 1966, and 4.8 x 10^5 by Townes 1971). We intend to extend the previous measurement range nearly two decades in Reynolds number to determine, for example, how does the skin friction coefficient C_f depend on Reynolds number at these high Reynolds numbers? Does the velocity profile continue to scale on inner and outer layer variables as it does at lower Reynolds numbers? What is the precise value of von Karman's constant, and how does it depend on Reynolds number? For the

turbulence field, what are the scaling laws for the spectra of the velocity fluctuations? Do the -1 and -5/3 regions continue to dominate the spectra? What are the scaling laws of turbulence at these high Reynolds numbers? Do the "universal" constants for the turbulence scaling laws proposed by Perry et al. (1989) apply at these Reynolds numbers? Can the assumption of small scale isotropy be made in high Reynolds number flows?

2. DETAILED DESCRIPTION OF COMPLETED WORK

2.1 Structure of Supersonic Boundary Layers

To identify the characteristics of the large-scale motions in supersonic turbulent boundary layers, hot wires were used to measure the streamwise fluctuating mass flux and normal fluctuating velocity. These signals were then conditionally sampled to give an approximate view of the flow-field associated with the average large-scale motion. The measurements were taken in the flow over a compression ramp where the upstream flow corresponded to a zero pressure gradient, Mach 2.9 boundary layer with Re = 81,000. The compression ramp was formed by a short region of concave surface curvature with a radius of curvature equal to 12 initial boundary layer thicknesses, and a total turning angle of 16^{o}. The overall pressure rise was 2.9,and the Mach number decreased to 2.13. Measurements upstream of the compression may be compared with similar subsonic results, and the data downstream of the curvature may be used to determine the effect of a strong adverse pressure gradient on the large-scale motions.

From the normal wire data, VITA events were found to correspond to mass flux fronts which extend over significant fractions of the boundary layer thickness and are inclined for the most part at an angle of about 50^{o} to the wall (Spina and Smits 1987). If the mass flux fronts are assumed to extend right across the layer, then the single point measurements can be used to determine the ensemble-averaged velocity field associated with the mass flux fronts, as follows. The VITA velocity signatures can be interpreted as a cut through the ensemble-averaged velocity field. The fronts are assumed to convect at a constant convection velocity throughout the layer, and this value is $0.9U_e$ in the zero-pressure-gradient case and $0.85U_e$ in the perturbed flow. The fluctuating quantities used to determine the ensemble-averages are relative to the local mean, so the difference between the local mean and the convection velocity is added to the ensemble-averaged velocities at each location, yielding a velocity which would be observed in a reference frame fixed to the mass flux front. Morkovin's (1962) Strong Reynolds Analogy must also be used here to convert instantaneous mass flux to instantaneous velocity (in related work by Smith and Smits 1990 the instantaneous validity of the SRA has been confirmed for this flow). The centers of the events are then displaced to correspond to the mean structure shape as were the isocorrelation contours derived from measurements made using two normal wires (see Spina et al. 1991 and Donovan et al. 1991 for details).

For the upstream boundary layer, the resulting velocity fields are shown in Figure 1a for positive events which correspond to the upstream side (back)

of a turbulent bulge. Here, the freestream velocity is from left to right. The mean structure shape is also indicated on these plots as determined from the double normal wire measurement discussed earlier. This field is essentially the velocity field seen as if convecting with the mass flux gradient interface of the ensemble-averaged structure. As discussed by Spina et al. (1991), the velocity vectors shown at the structure shape line have a non-zero streamwise component. The location of the center of the event determines this velocity and here it is rather arbitrary, being based upon a maximum in the short time variance. The "edge" of the motion is also rather difficult to define as a line. Nevertheless, this representation appears to capture the character of the ensemble-averaged flowfield, at least qualitatively. A comparison with similar measurements in a subsonic flow by Blackwelder and Kovasznay (1972) indicates a broad resemblance. The change in streamwise scale was discussed by Smits et al. (1989).

Similar velocity fields in the strongly perturbed flow are shown in Figure 1b. The rotating motion of the fluid downstream of the back is not as well defined and the upward velocity just before the mass flux gradient is much larger than in the unperturbed case. The fluid upstream of the interface turns away from the wall much sooner in this case as well. Throughout both fields there is an amplification in the normal velocity which is greater than that of the streamwise component, as evidenced by the steeper angle of most of the vectors. Clearly, the amplification of u and v is quite different.

The most recent work has focussed on three specific studies, which is receiving joint attention from the personnel of the Gasdynamics Laboratory and the Applied Physics Laboratory. They are:

(1) The evolution of large-scale density structures as they convect downstream. Double-pulsed Rayleigh scattering has been the principal tool. Single pulsed Rayleigh scattering has been widely used by us to study the instantaneous two-dimensional density cross sections in supersonic flow fields (see for example, Smith et al. 1989 and 1991). In double-pulsed Rayleigh scattering, a Nd:YAG laser is pulsed twice, and two successive images of the density field are recorded. The interval between the two pulses can be varied from about 12 us to about 100 us. The images can be double-exposed onto a single camera, or recorded using two separate cameras. In the results presented here, the Rayleigh scattering was performed in the visible, at a wavelength of 532 nm. Results have been obtained which cover a range of time intervals. Correlations with simultaneous hot-wire density measurements are being evaluated. Similar results obtained in a low Reynolds number incompressible turbulent boundary layer will also be used for purposes of comparison.

(2) Filtered Rayleigh scattering to study the instantaneous velocity distribution in a plane. In filtered Rayleigh scattering, a molecular filter window is used in combination with a tuneable laser (in this case, an iodine absorption cell and a injection-locked Nd:YAG laser) to determine the Doppler shift of the molecular scattering centers (see Miles and Lempert 1990).

(3) "RELIEF" measurements of the instantaneous velocity distribution along a

line, using the vibrational excitation of oxygen molecules (Miles and Lempert 1990).

2.2 Shock Wave Boundary Layer Interactions

In the study of the interaction between turbulence and shock waves, we have used the Rayleigh scattering technique to visualize the instantaneous density field in a variety of shock wave/boundary layer interactions, including nominally two-dimensional interactions generated by a 16^o and 24o compression corners, and by the reattachment of a free shear layer on a 20^o ramp, and two different three-dimensional interactions: one generated by a blunt fin with a circular leading edge, and another by a sharp fin at a 20^o angle of attack.

The experiments in the 24^o compression corner interaction indicated that the large scale motions observed in the incoming boundary layer can interact strongly with the shock wave, as shown in some of the images obtained by Smith et al. (1991). It appears from these images, and the work by Marshall and Dolling (1990), that the unsteady shock motion is closely coupled with the strength and frequency content of the incoming boundary layer structure. As far as we know, these images are the first to reveal the instantaneous shock structure, and the first to show the direct influence of the turbulence on the unsteady shock motion. At this stage, the particular characteristics of the turbulence that result in the strong coupling is not known, although we suspect that only large motions, with a high degree of coherence can interact directly with the shock. Further data analysis may lead to deeper insights. For example, image processing techniques can be used to generate space correlations of the fluctuating density field, and reveal the dynamic connection between the incoming motions, the shock motion, and the turbulence distortion.

When the plane of light is tilted so that it makes an angle of about 20^o with the plane of the ramp, a most remarkable wrinkling of the reattachment shock is made visible (Figure 2). This visualization of the instantaneous wrinkling of the shock sheet was suspected to occur on the basis on spanwise wall pressure measurements, but this image provided the first direct evidence of this phenomenon.

The more recent work has concentrated on a study of the shock-turbulence interaction occurring in the reattachment zone of a supersonic free shear layer, with the following aims:

(1) To investigate the mechanisms which cause the unsteady wall-pressure fluctuations in shock wave turbulent shear layer interactions and to find means to reduce the magnitude of the fluctuating pressure loads by controlling the unsteady shock motion. This particular task was additionally supported by NASA Langley Research Center under Grant NAG-1-1072.

(2) To find means of increasing large-scale mixing in a supersonic free shear layer. In the shear layer studied here, the convective Mach number is close

to one, and the growth rate is only one-third the corresponding growth rate observed in the incompressible case.

(3) To study methods for controlling the size and shape of separation bubbles in supersonic speed by modifying the free shear layer dynamics. This may result in the improved performance of flaps and other control surfaces for supersonic flight, and the possibility of increasing the angle of attack of airfoils operating at supersonic speeds.

In current work, we are using three-dimensional patterns of blowing in a direction normal to the main flow direction as a control device. In our effort to increase the mixing in the free shear layer, the results thus far (Poggie et al. 1992) indicate that this technique is very successful, and currently we are trying to implement piezo-electric actuators to enable active control of the blowing. We hope to make similar progress in our efforts to reduce the unsteady pressure loading near reattachment in the coming year.

We have also applied double-pulsed Rayleigh visualization to study the distortion of the incoming boundary layer turbulence as it passes through a shock in a shock wave boundary layer interaction generated by a 16° compression corner. The distortion is seen to be dramatic, although specific features of the motion are maintained throught the distortion (see Figure 3). Further analysis is in progress but these pictures provide the first direct evidence of the instantaneous nature of a shock-turbulence interaction.

2.3 Reynolds Number Effects

One of the most interesting observations made when comparing supersonic and subsonic boundary layers is that there appears to be an order-of-magnitude decrease in the rate of decay of the large scale motions seen between low subsonic and high supersonic flows. Consider the measurements of the longitudinal space-time correlations for optimum time delay by Favre et al. (1957, 1958) in subsonic flow, and Owen and Horstman (1972) at Mach 7.2: the longitudinal distance to the point where the correlation falls to a level of 0.5 at y/ = 0.15 for the supersonic data gives a value ten times larger than the subsonic data. Recently, we have postulated that these differences may be due to the large changes that occur in fluid properties across high Mach number boundary layers (Smith and Smits 1991, and Smits 1991). If the boundary layer is composed in essence of high-aspect ratio hairpin-like structures, as suggested by Head and Bandyopadhyay (1981), and if the spanwise scale is set by the fluid properties near the wall, and their rate of decay is dictated by the local fluid properties, then we would expect to see a much slower rate of decay in high Mach number flows where the kinematic viscosity decreases with distance from the wall.

More recent work has been part of a joint effort involving Brasseur at Penn State and Sreenivasan at Yale. Some aspects of the effects on Reynolds number on turbulent boundary layer behavior that are being emphasized are: (a) the outer structure, its origin, maintenance and interaction with the small scale; (b) the role of the forcing produced by the inner structure on the

stability and coherence of the outer structure, especially the way in which these latter aspects differ from those in free shear flows; (c) the development and use of new techniques in experimentation; (d) the development and use of interactive graphics-based techniques of analysis; (e) the structural relationships and relative dynamical significance of intense but infrequent events on the one hand, and small amplitude but pervasive fluctuations on the other; (f) the quantification of loosely-used concepts such as 'dynamical significance' (for example in maintaining the flow); (g) the modeling of flow dynamics by use of multifractal, wavelet, and Fourier analysis, and their interrelationships; (h) the understanding of the mixing and dispersion of passive scalars, especially with a view to unraveling the relationship between structures within the concentration field and those in the velocity field; (i) the effects of compressibility on several of these issues including the effects of fluid property variations; (j) the concurrent analysis of experimental and numerical data.

For the higher Reynolds number cases, the experiments at Princeton are providing data at a Reynolds numbers of 4,600, and 13,200, and previous work by Alving (1988) provide data at R of 5,000. These Reynolds numbers are not extraordinarily high, but all data are at two reasonably widely spaced Reynolds numbers, they are time-resolved, and include spatial correlations in all three directions. The data are available upon request. Similar measurements at Yale will yield data in the range R between 1000 and 5000, thereby providing a reasonably extensive range of Reynolds numbers to establish scaling laws. The data are being analyzed, in different ways, by all three co-investigators, and the data will continue to be made available as further measurements are completed.

Some progress has been made in understanding the effect of Mach number on turbulent boundary layers, and there is some hope that data taken in supersonic flows may be useful for determining Reynolds number effects. The advantage of using high speed data is that the Reynolds numbers can be very much higher than usually encountered in similar incompressible flows. Work is in progress.

Rough wall boundary layers, at wall distances large compared with a typical roughness height, approximate the infinite Reynolds number limit. At both Yale and Princeton, we are exploring the currently available data and considering the value of additional measurements rough wall boundary layers as a potentially useful complement to our current work.

The low Reynolds number studies at Princeton have concentrated on analyzing the full three-dimensional, time-evolving scalar field at the same Reynolds numbers used in the PIV studies of boundary layers at Yale (R of 700 and 1300). Preliminary work at these Reynolds numbers has been completed using a smoke tunnel, but current work is concentrating on a more detailed study over a larger volume using a water tunnel (Delo and Smits 1993). Figures 4 and 5 show some images obtained in this flow at a Reynolds number of 525. Preliminary visualizations of the effects of roughness in a low Reynolds number incompressible flow are also in progress.

APPENDIX A: Publications Acknowledging Grant 89-0420

BOOKS

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APPENDIX B: Personnel and Degrees Granted

The Grant has supported the following faculty and staff members:

Professor Alexander J. Smits (Principal Investigator);
Professor Richard B. Miles;
Professor Seymour M. Bogdonoff;

Dr. Walter Lempert;
Dr. Kamal Podar;
Dr. Ivan Glesk;

Robert Bogart (Technical Specialist);
William Stokes (Technical Specialist);
Phil Howard (Technical Specialist);
Richard Gilbert (Computer Specialist).

The activities were supported by 14 research students. Their names are: A. Alving, E. Fernando, J. Goldstein, J. Poggie, M.W. Smith, D. Smith, R. Smith, B. Zhang, D. Zhou, J. Forkey, E. Spina, J. Donovan, W. Konrad and M. Zagarolla. Ten of these students are U.S. Citizens.

During the period of the subject grant, 5 students supported by the grant received the Ph.D. degree. They were Amy Alving (Technical University of Berlin, now Assistant Professor University of Minnesota), Eric Spina (Assistant Professor, Syracuse University), Emerick Fernando (Flow Research, now Microsoft, Seattle), John Donovan (McDonnell-Douglas, St. Louis), Mike Smith (NASA Langley Research Center), Doug Smith (post-doc, IMST Marseille), Randy Smith (ARL, University of Texas, Austin), Wolfgang Konrad (BMW/Rolls-Royce, Munich). Three students received the MSE degree. They were J. Goldstein (UTRC, Hartford, CT), J. Poggie (Ph.D. studies, Princeton under the Palace Knight Program) and M. Zagarolla (Ph.D. studies, Princeton).

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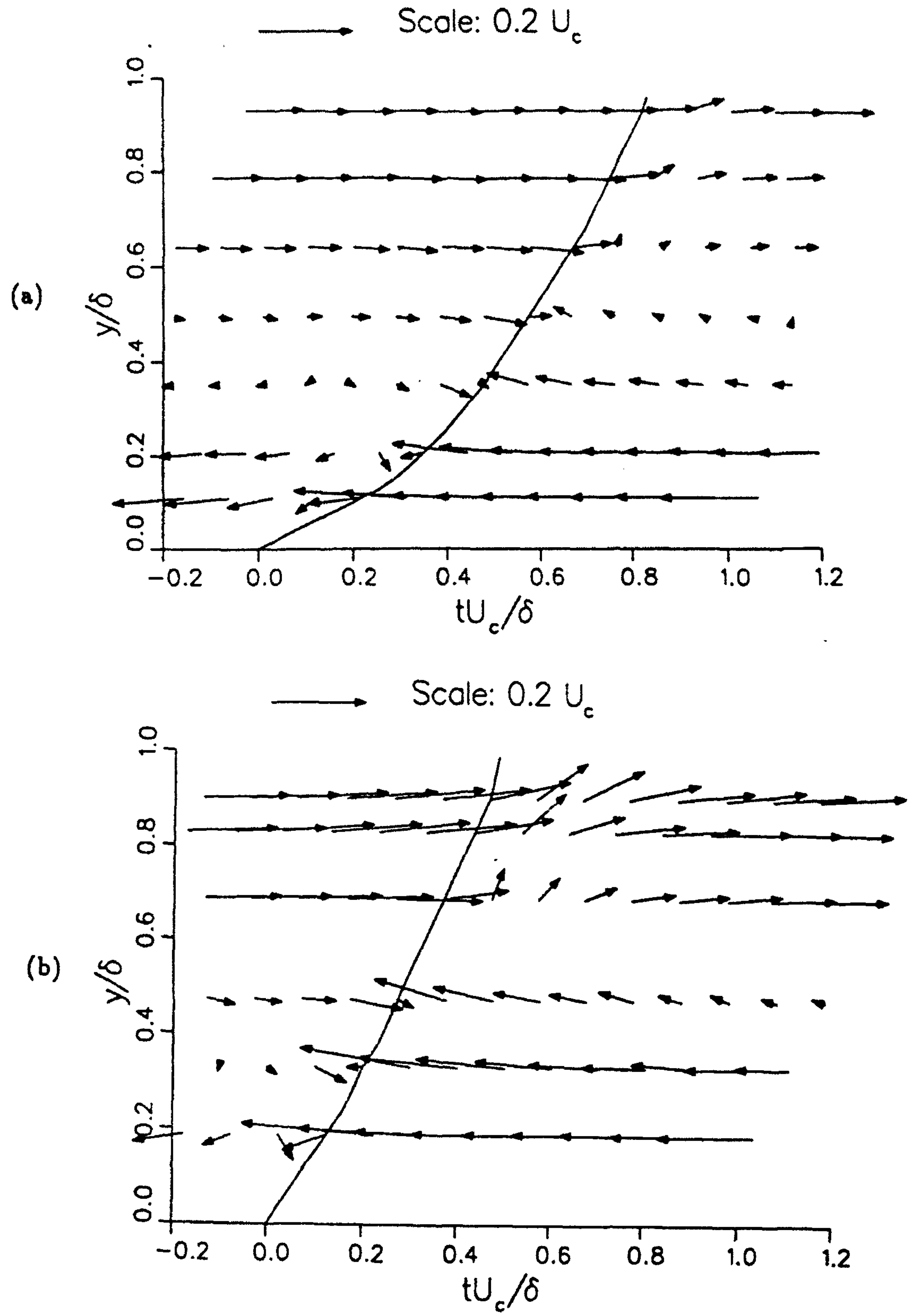


Figure 1 : Average flowfield in the region of the positive mass-flux gradient as seen in a reference frame moving at the convection velocity for the upstream boundary layer (a), and the boundary layer at $x/\delta_0 = 5.4$ (b).

Streamwise image of a reattaching free shear layer in an air flow. Flow is from right to left. The complicated shock structure near reattachment is clearly evident

Image of the attachment region of a free shear layer on a 20 ramp in an air flow. The laser sheet orientation is shown in Fig. 1. Flow is from top to bottom of the picture. Shocks show up as regions where the brightness increases (this is true as long as the temperature rise is relatively small). These images indicate that more than one shock is present in the reattachment region, and that they are strongly wrinkled by the incoming turbulence

Figure 2.

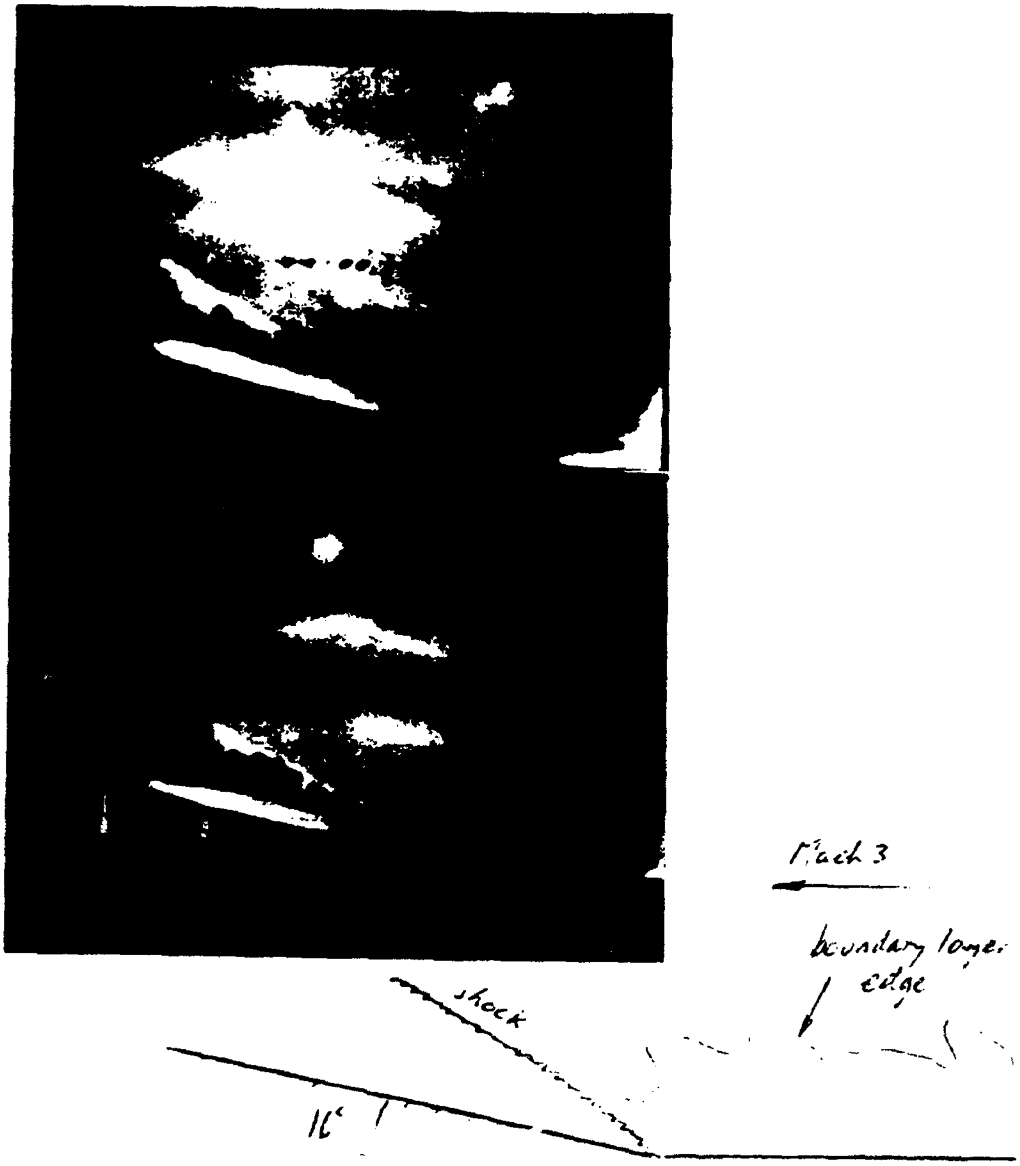
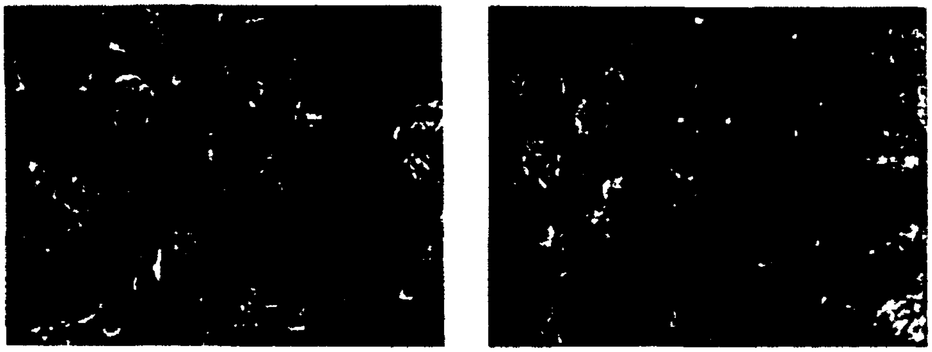
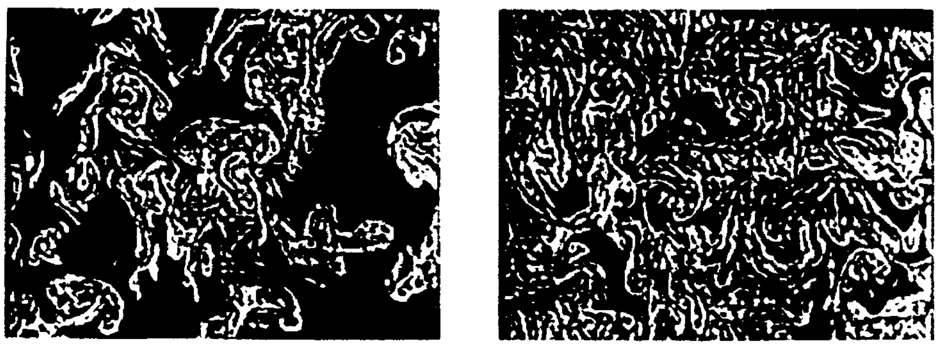


Figure 3. Sequential images of the density field in a Mach 3 shock wave boundary layer interaction generated by a 16° compression corner. The images were obtained using double-pulsed Rayleigh scattering, and the bottom image was taken 40 microseconds later than when the top image was taken.



(a) Image data at y+ = 192, y/δ =0.85 (b) Image data at y+ = 96, y/δ = 0.43

Two-dimensional images obtained in the water channel at a Reynolds number of 525. The images are parallel to the wall and flow is from top to bottom. The field of view is about 2.9 by 3.6 boundary layer thicknesses.



(a) Processed data at y+ = 192
y/δ = 0.85

(b) Processed data at y+ = 96
y/δ = 0.43

The data of Figure 5, after convolution with a Marr operator. The operator had a "diameter" of 6 pixels, or 8 wall units. Images have been stretched to fill the gray scale.

Figure 4.

Figure 5.